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Polaris B, an optical companion of Polaris (α UMi) system: atmospheric parameters, chemical composition, distance and mass

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ABSTRACT
We present an analysis of high-resolution spectroscopic observations of Polaris B, the optical companion of the Polaris Ab system. The star has a radial velocity V_r of $-16.6\,\mathrm{km\,s^{-1}}$ to $-18.9\,\mathrm{km\,s^{-1}}$, and a projected rotational velocity $v \sin i = 110\ \mathrm{km\,s^{-1}}$. The derived atmosphere parameters are: $T_{\rm eff}$=6900 K; $\log g = 4.3$; $V_{\rm t}$=2.5 $\mathrm{km\,s^{-1}}$. Polaris B has elemental abundances generally similar to those of the Cepheid Polaris A (Usenko et al. 2005a), although carbon, sodium and magnesium are close to the solar values. At a spectral type of $F3$ V Polaris B has a luminosity of 3.868 $\mathrm{L_\odot}$, an absolute magnitude of $+3.30^m$, and a distance of 109.5 pc. The mass of the star is estimated to be 1.39 $\mathcal{M}_\odot$, close to a mass of 1.38±0.61 $\mathcal{M}_\odot$ for the recently-resolved orbital periods companion Polaris Ab observed by Evans et al. (2007).

Key words: Stars: abundances – Stars: individual – Polaris B

1 INTRODUCTION

Polaris B (BD+88°7; SAO 305) is the nearest optical companion to the Cepheid binary Polaris Ab (α UMi) system. Its visual magnitude of $8^{m}_{.}60$, angular distance of $18''$ from Polaris, and spectral type of $F3$ V suggest that it is a physical main-sequence companion of α UMi (Fernie 1966; Turner 2005). Polaris A is itself a small-amplitude Cepheid with a spectroscopic binary companion, Polaris Ab, with an orbital period near 30 years (Roemer, 1965; Kamper, 1996; Usenko et al. 2005b). The main-sequence companion is $0''_{.}176$ from the Cepheid primary according to recent obervations by Evans et al. (2007). Two other optical companions, Polaris C and D (13 and 12^m, angular separations from Polaris A of $43''$ and $83''$, respectively, are also potential members of the multiple system (Fernie, 1966), although recent observations refute that suggestion (Evans et al., 2007). It would therefore be interesting to establish the atmospheric parameters and chemical composition of component B for comparison with those for the Cepheid Polaris itself — it is known that Cepheids progenitors are main-sequence B-stars, more massive and rapidly evolved stars than their F–type companions. It is particularly importnat to examine the “key elements” for yellow supergiant evolution — the CNO elements, sodium, and magnesium. The most detailed analysis of the chemical composition for Polaris is that in our earlier study (Usenko et al., 2005a). It is also an important exercise to establish the distance and mass of Polaris B using its spectroscopically-established $T_{\rm eff}$ and $\log g$ values, for comparison with the masses of the close companions: Polaris Ab and B.

2 OBSERVATIONS, ATMOSPHERIC PARAMETERS, RADIAL AND PROJECTED ROTATIONAL VELOCITIES

High-resolution CCD spectrum of Polaris B within the wavelengh ranges 4555–6000 Å have been obtained on June 2006 (HJD 2453904.879) using 6 m telescope BTA of the Special Astrophysical Observatory of the Russian Academy of Sciences with the high resolution echelle spectrograph NES (Panchuk et al. 2002). In combination both with CCD 2048 x 2048 pixels and with an image slicer (Panchuk et al. 2003), NES provides the resolutional power R≈60,000 within the wavelengh ranges 3500–6800 Å. Signal-to-noise ratio at the continuum level in each of 25 spectral orders exceeds 70. A Th–Ar lamp was used for the wavelength calibration.

We need to draw an attention for so called scattered light problem in this case of Polaris B. First Fernie (1966) was

confronted with difficulties in his photometrical observations when the scattered light from the primary component "..appreciably contaminated the light of the eight magnitude secondary...under the relatively poor seeing conditions that preveal in this climate". Afterwards Kamper (1996) noted that fibre-linked CCD observations are "ideal" since the small circular entrance aperture makes their "..easier to avoid contamination from Polaris A".

We have a lot of calculations of the radial energy distribution along stellar images of the 6 m telescope for different values of seeing. All calculations were made in approximation of a stellar images by the Lorentzian profiles. For details of the procedure see the paper of Diego (1985). In particular, at seeing $\beta = 3^{''}$ the weakening of the flux of a star located at distance $d = 18^{''}$ from the slit is equal to $\mathrm{X} = 6 \,\mathrm{x}\, 10^{-5}$ (10.5^m). We have just such a seeing in our observing run. It means that we can not register the scattering light of Polaris since it is known that we may register radiation of double stars if the difference of their magnitudes is not more than 2^m.

As known, Polaris A is a slow rotating yellow supergiant with sharp and narrow absorptional deep lines. Indeed, we do not see any spectral features (narrow absorptions) of Polaris A in the spectrum of Polaris B having very broad lines as a result of fast rotation. Therefore we can verify that scattered light influence from the primary component is insignificant.

Using the ECHELLE context of MIDAS modified by Yushkin & Klochkova (2005) for the case of observations with an image slicer, we extracted the spectra from the CCD images, subtracted bias, applied flat-field corrections, removed cosmic rays, performed the wavelength calibration, and summed up individual images. Further work with the spectra, including normalization to the continuum level, wavelength calibration and equivalent width measurements ($W_\lambda \leq 160$ mÅ), was done using the DECH20 package (Galazutdinov 1992).

3 MAIN PARAMETERS

Before the atmospheric parameters determinations we made the visual inspection of Polaris B spectrum, because it has a relatively high projected rotational velocity (see Fig. 1.)

Radial velocity measurements were carried out using H_β and 63 absorption lines of metals. The results are: $-16.6\,\mathrm{km\,s^{-1}}$ and $-18.9\pm3.6\,\mathrm{km\,s^{-1}}$, respectively. These data are close within the limits of errors to Kamper's (1996) result of $-14.7\pm1.2\,\mathrm{km\,s^{-1}}$. To evaluate the line blends for Polaris B, the spectrum synthesis technique was applied. This was performed with the help of SYNSPEC code (Hubeny et al. 1994). Projected rotational velocity was estimated by fitting the synthesized spectrum to observed one.

Before this procedure we have to set the preliminary estimates of effective temperature and gravity values. Using $(B-V) = 0.42^m$, $(U-B) = 0.01^m$ (Turner 2005) and $E_{B-V} = 0.034^m$ (Usenko et al. 2005a) from (U-B),(B-V) – $\mathrm{T_{eff}}$, $\log g$ calibrations (Castelli 1991), the preliminary values were $T_{\mathrm{eff}} = 6900$ K and $\log g = 4.5$. Starting with these atmosphere parameters and to avoid the scattered light influence from Polaris A we have use the synthetically generated H_β line profile and compared with the observed one. Finally we have found the best fit in case of $v \sin i = 110\,\mathrm{km\,s^{-1}}$, $T_{\mathrm{eff}} = 6900 \pm 50$ K and $\log g = 4.3 \pm 0.15$ (see Fig. 2).

The next step was to specify the surface gravity by adopting the same iron abundance of the FeI and FeII lines (with a mean uncertainty of 0.15 dex). And, the microturbulent velocity by assuming abundances of the FeI lines independent of the equivalent width W_λ (a mean error of $0.25\,\mathrm{km\,s^{-1}}$). All the atmosphere models and chemical composition were calculated using our version of the WIDTH9 code on the basis of the Kurucz (1992) grid with the "solar" log gf values, adopted from Kovtyukh & Andrievsky (1999). As seen we had a happy choice for our second shoot to detect the surface gravity, – FeI and FeII abundances gave an equivalent results in case of $\log g$=4.3.

Finally, we have obtained for Polaris B the following values of parameters: $\mathrm{T_{eff}} = 6900$ K; $\log g = 4.3$; $V_{\mathrm{t}} = 2.5\,\mathrm{km\,s^{-1}}$; $V_r = -16.6\,\mathrm{km\,s^{-1}}$ (H_β) and $-18.9\,\mathrm{km\,s^{-1}}$ (metallic lines); $v \sin i = 110\,\mathrm{km\,s^{-1}}$.

4 CHEMICAL ABUNDANCES

Since Polaris B spectrum displayed the absorptional lines spreading by a high projected rotational velocity, we had to select unblended ones. In Table 1 the derived mean element abundances for Polaris B are given in comparison with ones of Polaris the Cepheid (Usenko et al. 2005a).

A comparison of chemical abundances of the both components displays some interesting features. At about an equal (within the limits of mean errors) iron, $\alpha-$, Fe-group (excepting manganese) and s-process elements abundances for the both stars, Polaris B demonstrates solar carbon content, thereas Cepheid Polaris A has obvious deficit, conditioned by its possibly third or fifth Cepheids instability strip crossing (Usenko et al. 2005a). The same cause is noticeable for sodium and magnesium, – its content for Polaris B is close to solar one too ($see Fig. 3$).

5 RADIUS, LUMINOSITY, DISTANCE AND MASS

Since we can estimate a radius value for $F3\,\mathrm{V}$ spectral type main-sequence near $1.38\,\mathrm{R}_\odot$ (Straižys 1982), therefore its luminosity is $3.868\,\mathrm{L}_\odot$, absolute magnitude $\mathrm{M_V} = +3.30^m$. Using $A_\mathrm{V} = 0.102^m$ from Usenko et al. (2005a) we can obtain the distance $D = 109.5$ pc. This result has an ideal agreement with Kamper's (1996) one of 110 pc, obtained by astrometrical methods.

According to Straižys (1982) the mass for such star is equal to $1.31\,\mathcal{M}_{\odot}$, therefore $\log(L/L_{\odot}) \approx 4\log(M/M_{\odot})$ equation gives $1.4\,M_{\odot}$. Using our $\log g = 4.3$, and radius $1.38\,\mathrm{R}_{\odot}$ we can obtain a value of $1.39\,\mathcal{M}_{\odot}$. As seen, our mass is satisfactory close to these two different sources of mass values.

6 CONCLUSIONS

We can summarize the results of our investigation as follows.

(i) Radial velocity values for Polaris B are close to $\gamma = -15.9 \pm 0.06\,\mathrm{km\,s^{-1}}$ of Polaris A system.

(ii) High projected rotational velocity $v \sin i = 110\,\mathrm{km\,s^{-1}}$ is an evidence that system is young and Polaris B is likely to be single, since most binaries of $A - F$ types have slow rotation, the angular momentum being tied up in orbital motion. Moreover, the rapid rotation's observation could be mean that we see the star nearly equator-on.

(iii) Atmosphere parameters, obtained for Polaris B are typical for $F3$V star.

(iv) The majority of Polaris B chemical elements shows abundances, equal to Polaris A and close to solar one. But carbon and sodium in Polaris B close to solar content, therefore Polaris A demonstrates a typical for the first dredge-up yellow supergiants deficit of C and Mg and overabundance of Na (Usenko et al. 2005a). Therefore we are eye-witnesses of evolutional history of two stars with different masses in the same stellar system.

(v) Absolute magnitude $+3.30^m$ is equal to one from Fernie (1966). Spectroscopically determined effective temperature 6900 K combinating with radius of $1.38\,\mathrm{R}_{\odot}$ give the distance near 109.5 pc that agrees with Kamper's (1996) 110 pc one's. This result is quite unexpected, because Turner (2005) denoted 101 ± 3 pc to this object and Polaris system as a whole. Whereas HIPPARCOS parallax (ESA 1997) and optical interferometry (Nordgren et al. 1999) results give 132 ± 9 pc to the Polaris A.

(vi) The obtained mass of Polaris B near $1.39\,\mathcal{M}_{\odot}$ has been founded as unexpected close to one of Polaris Ab spectroscopic companion, – $1.38 \pm 0.61 M_{\odot}$ (Evans et al. 2007). The last one is, probably, a main-sequence star of earlier than $F4$V spectral type (Evans et al. 2002).

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Table 1. Average elemental abundances for Polaris B in comparison to Polaris A (Usenko et al. 2005a)

Element	Polaris B			Polaris A	
Element	[El/H]	σ	NL	[El/H]	σ
C I	−0.00	0.05	4	−0.17	0.10
Na I	+0.03	–	1	+0.09	0.11
Mg I	+0.04	0.12	2	−0.21	0.12
Si I	+0.15	0.18	2	+0.10	0.09
S I	−0.01	–	1	+0.09	0.17
Sc II	−0.04	0.04	2	−0.02	0.11
Ti I	+0.13	0.20	3	+0.09	0.17
Ti II	−0.01	0.21	2	+0.05	0.08
Cr I	+0.11	0.20	6	+0.05	0.20
Cr II	+0.02	0.16	3	+0.06	0.13
Mn I	+0.29	0.06	2	−0.13	0.14
Fe I	+0.05	0.14	24	+0.07	0.12
Fe II	+0.08	0.25	3	+0.07	0.08
Ni I	+0.03	0.12	11	−0.06	0.14
Cu I	−0.07	–	1	+0.13	0.14
Y II	+0.21	0.18	2	+0.17	0.15
Zr II	+0.26	–	1	+0.13	0.16
Ba II	−0.11	–	1	–	–
Ce II	−0.04	0.13	2	+0.07	0.17
Nd II	+0.15	0.12	3	+0.06	0.13

NL – number of lines

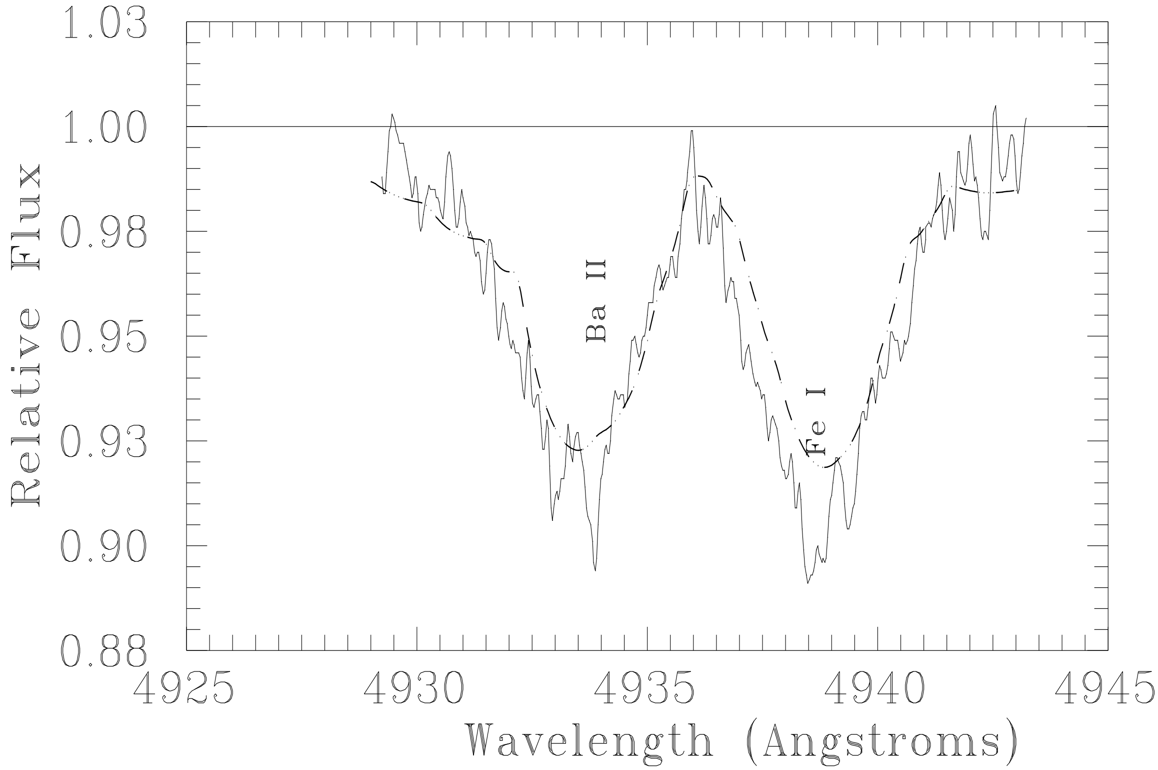

Figure 1. Fragment of Polaris B spectrum in range of $\lambda\lambda$ 4930–4943 ÅÅ. Synthetic spectra (dashed line) calculated in case of of $T_{\rm eff} = 6900$ K, $\log g = 4.3$ and $v \sin i = 110\,{\rm km\,s^{-1}}$

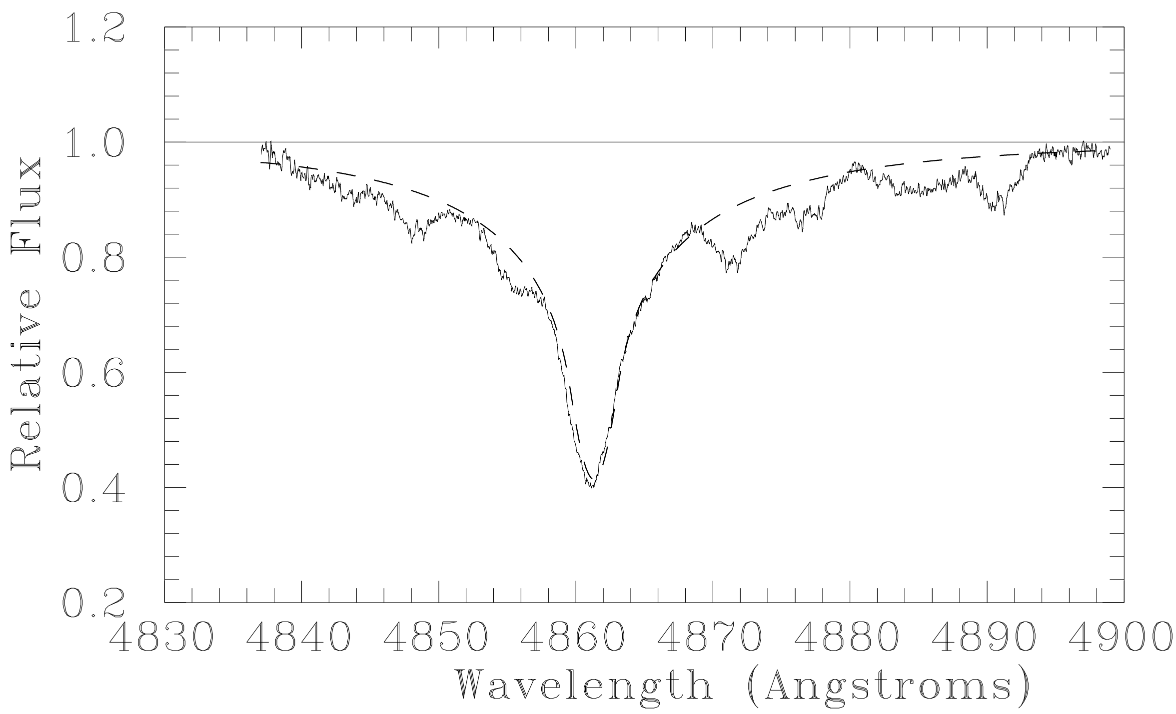

Figure 2. The fit between observed and synthetic spectra (dashed line) for Polaris B region near H_β line in case of $T_{\rm eff} = 6900$ K, $\log g = 4.3$ and $v \sin i = 110\,{\rm km\,s^{-1}}$

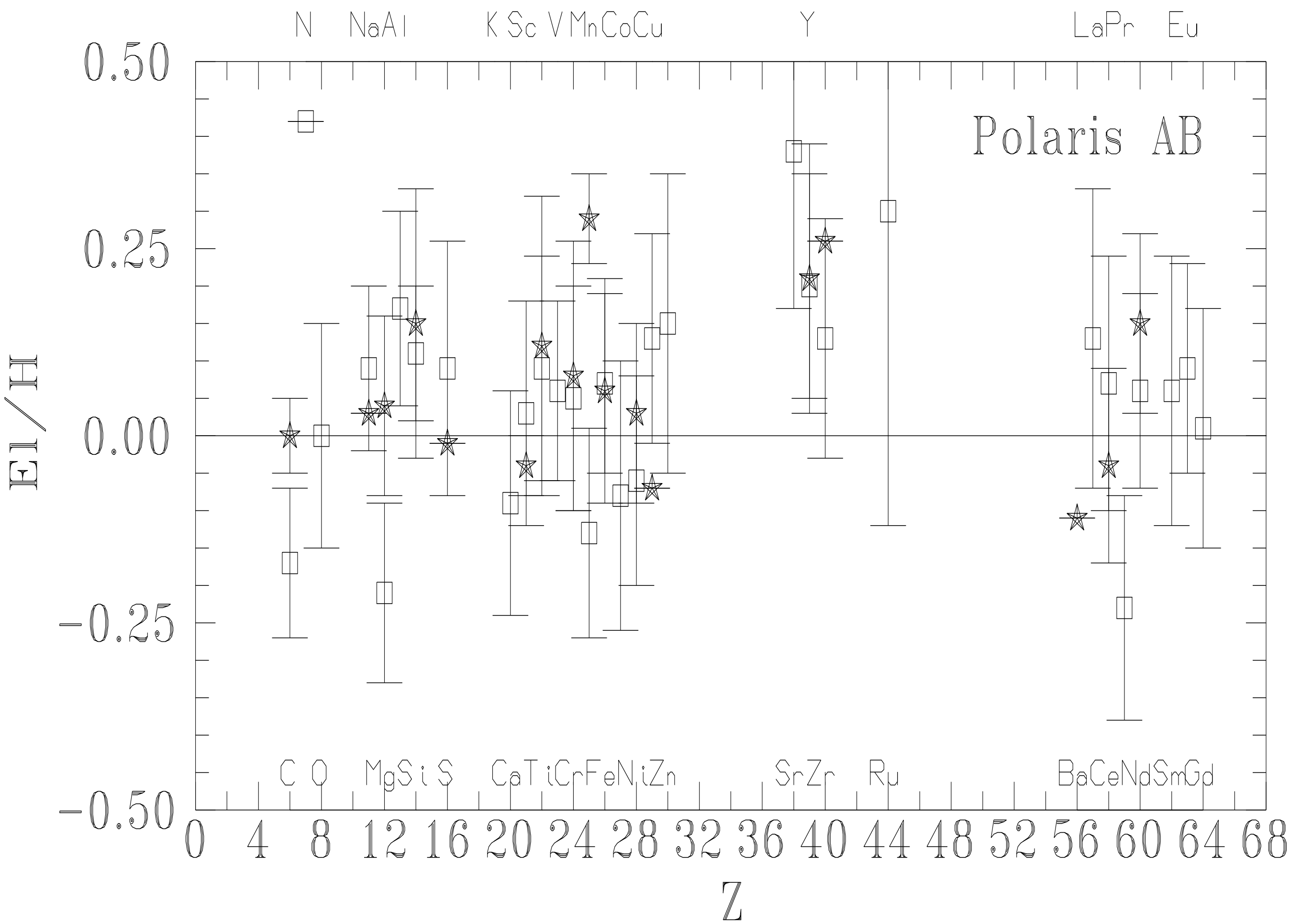

Figure 3. Chemical abundances for Polaris A (squares) and Polaris B (filled stars)